High-efficiency large-angle Pancharatnam phase deflector based on dual-twist design

Kun Gao[1], Colin McGinty[1], Harold Payson[2], Shaun Berry[2], Joseph Vornehm[2], Valerie Finnemeyer[2], Brian Roberts[2], Philip Bos[1*]

[1]Liquid Crystal Institute and Chemical Physics Interdisciplinary Program, Kent State University, Kent, OH

[2]M.I.T. Lincoln Laboratory, 244 Wood Street, Lexington, MA

Corresponding author: pbos@kent.edu

Pancharatnam made clear the concept of a phase-only device based on changes in the polarization state of light[1]. It was later shown that this concept could be used to make an optical device that could simulate a prism. We have previously shown through simulation that an optical beam deflector based on Pancharatnam phase can provide high efficiency with up to 80° deflection using a dual-twist structure for polarization state control[2,3]. In this report, we demonstrate that its optical performance is as predicted and far beyond what could be expected for a conventional diffractive optical device. We provide details about construction and characterization of a ±40° beam steering device with 90% diffraction efficiency based on our dual-twist design at 633nm wavelength.

A device of this type is sometimes called a circular polarization grating because of the polarization states of interfering light beams that are used to fabricate it by polarization holography[4]. Here we will call it a Pancharatnam phase device to emphasize the fact that the phase of diffracted light does not have a discontinuous periodic profile but changes continuously. Previous approaches to provide large angle optical beam steering devices have not been able to provide the required performance. Bragg gratings can provide large angle beam deflection; however, the angle of incidence and wavelength are restricted by the Bragg condition. Optical phased arrays that have a saw tooth phase profile with an optical depth of one optical wave have been shown to also provide high efficiency, but their efficiency drops if the deflection angle is larger than about 15°[5]. Devices based on Pancharatnam phase have been proposed by Crawford, *et al.* who have shown a basic method for producing them using liquid crystal (LC) based technology[6]. Broer and Escuti then showed excellent devices from this method[7]. Recently, further demonstrations attempting to overcome the limitations of previous approaches have been reported, with an even wider range of potential applications[8-13].

Figure 1a shows the schematics of a thin-film beam deflector based on Pancharatnam phase. It can deflect the incident wave of light (λ) to a certain diffraction angle (θ_{diff}), determined by diffraction grating equation $\sin(\theta_{\mathrm{diff}}) = \lambda/\Lambda$. Here, Λ is called the half-pitch, which is defined as the distance over which liquid crystal molecules are rotates by π radians about y axis. The LC orientation does not change along the y direction. We will call this basic type of device a conventional Pancharatnam phase deflector (c-PPD).

From paraxial analysis[14], the relation between input light and output light at one position in the aperture of a c-PPD can be expressed as,

$$[\boldsymbol{E_{out}}] = [\boldsymbol{M}(\boldsymbol{\Gamma}, \boldsymbol{\varphi})][\boldsymbol{E_{in}}], \quad (1)$$

with $[\boldsymbol{M}(\boldsymbol{\Gamma}, \boldsymbol{\varphi})] = [\boldsymbol{R}(-\boldsymbol{\varphi})]\begin{bmatrix} \boldsymbol{e^{-i\Gamma/2}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{e^{i\Gamma/2}} \end{bmatrix}[\boldsymbol{R}(\boldsymbol{\varphi})]$.

Here, φ is the angle between the optical axis and the z axis, and $[R(\varphi)]$ is a rotation matrix.

If considering a circularly polarized light input $\begin{bmatrix} \boldsymbol{E_{z-in}} \\ \boldsymbol{E_{x-in}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{\pm i} \end{bmatrix}$,

the output is

$$\begin{bmatrix} \boldsymbol{E_{z-out}} \\ \boldsymbol{E_{x-out}} \end{bmatrix} = \boldsymbol{cos}\frac{\boldsymbol{\Gamma}}{2}\begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{\pm i} \end{bmatrix} - \boldsymbol{isin}\frac{\boldsymbol{\Gamma}}{2}\boldsymbol{e^{-i(\mp 2\varphi(x))}}\begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{\mp i} \end{bmatrix}, \quad (2)$$

where phase retardation $\Gamma = \frac{2\pi\Delta nd}{\lambda}$, and Δn is birefringence. When the phase retardation meets the half-wave condition ($\Gamma = \pi$), the output will be simplified to

$$\begin{bmatrix} \boldsymbol{E_{z-out}} \\ \boldsymbol{E_{x-out}} \end{bmatrix} = -\boldsymbol{ie^{-i(\mp 2\varphi(x))}}\begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{\mp i} \end{bmatrix}. \quad (3)$$

This equation makes it clear that light of the opposite handed circular polarization from the input light achieves a phase shift determined by the angle φ, which is the angle the director (the local average orientation of the liquid crystal molecules) is rotated about the axis normal to the plane of the device (the y axis in Fig. 1a). In a beam deflector, $\varphi(x)$ is a linear function of x, namely, $\varphi(x) = 180° \cdot x/\Lambda$ as shown in Fig. 1a. It has been shown that a c-PPD with a small deflection angle can have ~100% diffraction efficiency[2,15] (see Methods for details). Unfortunately, when the diffraction angle becomes large, the efficiency goes down quickly, especially for low birefringence materials.

We propose the use of a dual-twist structure to improve the steering efficiency as shown in Fig. 1b. The phrase "dual twist" refers to the fact that the LC director spirals about the y axis both in-plane (dependent on the x position) and out-of-plane (dependent on the y position). Our design consists of two such dual-twist Pancharatnam phase deflectors (DTPPDs), with equal in-plane periodicity and equal but opposite out-of-plane twist angles. The twist angle in these two DTPPDs is mirror symmetric. Each DTPPD has the thickness of the half-wave plate (d) at the designed wavelength. Such a dual-twist structure has been proposed earlier by Escuti, *et al.* for achromatic application as a broadband beam deflector[16,17]; Li, *et al.* also proposed a high-efficiency broadband device with a wide incident angle range[14]. However, these earlier applications are limited to small diffraction angles, i.e., small deflection angles.

Here we demonstrate a dual-twist structure that provides the predicted large angles of deflection with high efficiency by experimentally pushing the limit of the half pitch Λ to ~1 µm, allowing fabrication and characterization of a device with a 40° diffraction angle. With this device, we demonstrate a high-efficiency beam steering with 80° field of view (FOV), which is controlled only by changing handedness of circularly polarized input light.

Following the method proposed by Crawford, *et al.*[6], we choose the azo dye Brilliant Yellow (BY) as the alignment layer for the reactive mesogen (RM257). The RM257 layer thickness is chosen to provide the desired half-wave retardation. Figure 2a shows a schematic of the polarization holography setup to expose the photo-alignment layer. The blue laser beam is first expanded to 5 mm diameter by a beam expander, then split into two optical paths with opposite circular polarizations. The recording angle can be calculated from $\Theta_{\mathrm{rec}} = 2\sin^{-1}(\lambda_{\mathrm{rec}}/2\Lambda)$, where λ_{rec} is the wavelength used for recording. In our experiment, λ_{rec}=457 nm, Θ_{rec}=~27°. To visualize the resulting interference pattern, a linear polarizer can be placed in front of a CCD camera with a 20x objective lens that is focused on the plane where the BY sample is placed. Then the interference pattern can be directly seen by the camera as shown in Fig. 2b. During the exposure, the substrate with the photo-alignment layer is placed at the position where two interfered beams both have the same 5 mm diameter and the same power. The substrate is then exposed for 8 minutes. Right after this process, we can see a chromatic reflection from the exposure area under white light as shown in Fig. 2c.

To provide a comparison with previously reported devices, we fabricated 20° and 40° deflectors. The 20° deflector achieves an efficiency of 97% as shown in Fig. 3a. As a comparison, we also show the results of 40° *c*-PPD in Fig. 3b. Its efficiency is lower than 50%, as predicted by the simulation results (see Methods for details). In order to find the best twist angle for an optimized dual-twist device, we perform a finite-difference time-domain (FDTD) simulation. For our case of RM257 with birefringence Δn ~ 0.14[10], we found a twist angle of ~105° to achieve the best efficiency (see Methods for details).

Experimentally, we find that by doping the RM257 material prior to spin coating with 0.65% of the chiral dopant ZLI-811 (S-811) from Merck provides the highest deflection efficiency of a single DTPPD when the thickness of the device is optimized by controlling the number of layers of deposited RM257, as shown in Fig. 4a. Figure

4b shows the effect of the optimized layer on incident light with left circular polarization (LCP) or right circular polarization (RCP).

When this single DTPPD is combined with a second one that is constructed by using a chiral dopant ZLI-3786 (R-811) with the opposite twist, the structure of Fig. 1b is realized. The resultant device can deflect light to +40° or −40° by changing the input polarization state of light from RCP to LCP as shown in Fig. 5. The measured efficiency of this device is 90%, very close to the result of 92% predicted by FDTD simulation. (See Methods for details.)

In conclusion, we have demonstrated a ±40° beam steering device with high-efficiency based on a Pancharatnam phase deflector with a dual-twist structure using simulations and experiments. While these devices have a strong wavelength dependence, this report demonstrates that a device with a structural periodicity near the wavelength of light can deflect light to large angles with efficiencies close to 100%. The demonstrated dual-twist design and fabrication procedure opens the possibility for making a high-efficiency wide-angle beam steering device, a lens with *f*-number less than 1.0, and a wide range of other potential applications in the optical and display industries.

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Author Contributions

P. B. proposed the idea of high-efficiency large-angle Pancharatnam phase deflector. K.G. built the holographic set-up, fabricated the real devices, performed measurements and FDTD simulation as well as wrote this manuscript with the help and supervision of

P. B. and H. P. Also, C. M. gives the help in the sample preparation and fabrication. S. B., J. V., V. F., B. R. discussed the results, gave suggestions, and contributed to the manuscript.

Competing financial interests

The authors declare no competing financial interests.

Methods

FDTD simulation. Yee's grid for FDTD simulation is an effective method of computing electromagnetic problems[18]. By directly solving coupled Maxwell's curl equations with few approximations, FDTD is also a robust method for dealing with light propagation problems in birefringent media[19,20]. It has been shown that FDTD can provide precise simulation results for Pancharatnam phase devices[15,21]. Therefore, we have chosen the FDTD method as our simulation tool to study the efficiency of large deflection angle devices. The simulation program is written in BOSLAB at the Liquid Crystal Institute and used for the simulation of DTPPD in variable conditions. The details of FDTD simulation and results generated in this report can be seen in Supplementary Information.

Fabrication and measurements. To prepare photo-alignment films, BY material was dissolved in dimethylformamide (DMF) solution with fixed concentration of 1.5% by weight. The solution was spin-coated onto substrates at 800 rpm for 5 seconds and then 3000 rpm for 30 seconds. The films were dried in an oven at 120˚C for 30 minutes. This layer is a thin photo-sensitive film showing anisotropic response to the polarization axis of light. We then use polarization holography alignment technique to expose BY, and coat several layers of 10% RM257 dissolved in Toluene until it achieves the thickness of half-wave plate at 633nm wavelength (Supplementary Fig. 7). An efficiency test was performed after each layer of RM257 coated to monitor if it has reached the maximum (Supplementary Fig. 8). We stopped coating at the 10th layer of RM257 when the chiral dopant is added for a single optimized 40° DTPPD. Then we measured both the transmitted and reflected intensity of light for each order in ±40° beam steering by combining 1st and 2nd DTPPDs together to realize the proposed design shown in Fig. 1b. The intrinsic efficiency is calculated based on the total transmission of +1st, 0, −1st-orders (Supplementary Table 1&2).

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Figure Legends

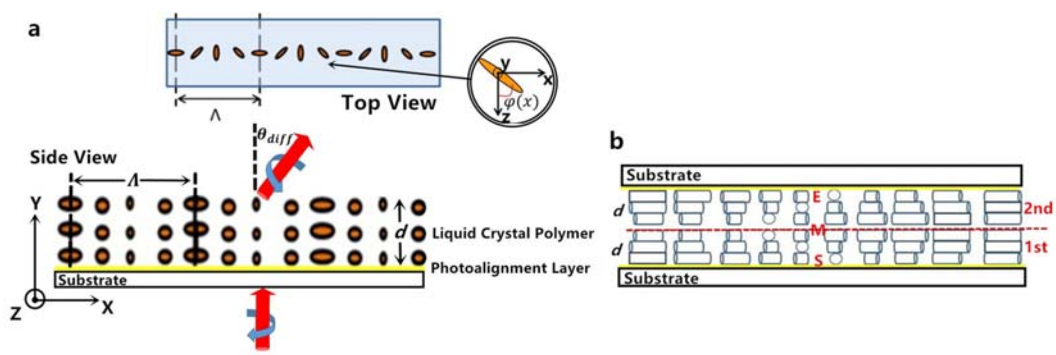

Figure 1 | Concept of Pancharatnam phase deflector. a, A *c*-PPD in its side-view and top-view. The inset shows a molecular alignment of reactive mesogen (RM). **b,** A revolutionary dual-twist design in its side view with two combined DTPPDs, in which the twist angle is mirror symmetric. S/M/E correspond to the position of evolution of polarization state on the Poincaré sphere (see Methods for details).

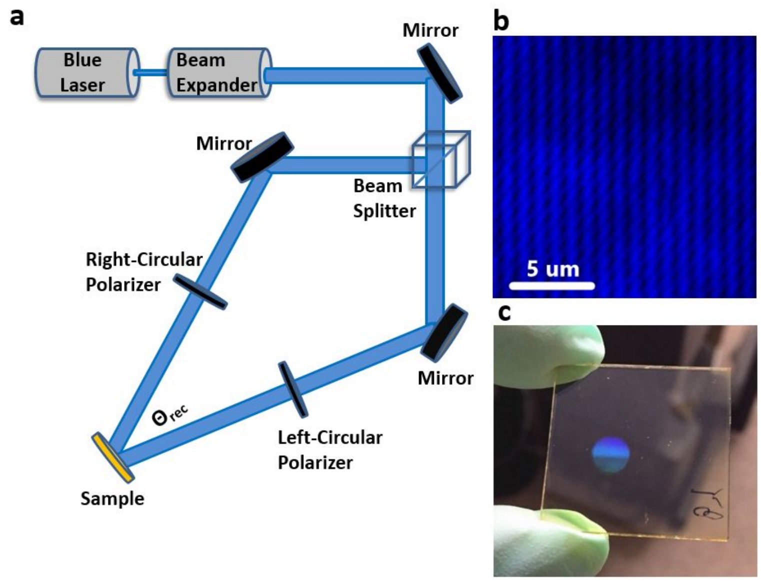

Figure 2 | Experimental setup for holographic exposure. a, The blue laser (457nm) with 200mW power is used to expose the photo-alignment layer and two coherent laser beams with the same intensity are interfered at the place of sample. **b,** Observation of the interference pattern using a camera. **c,** The appearance of written BY immediately after the exposure.

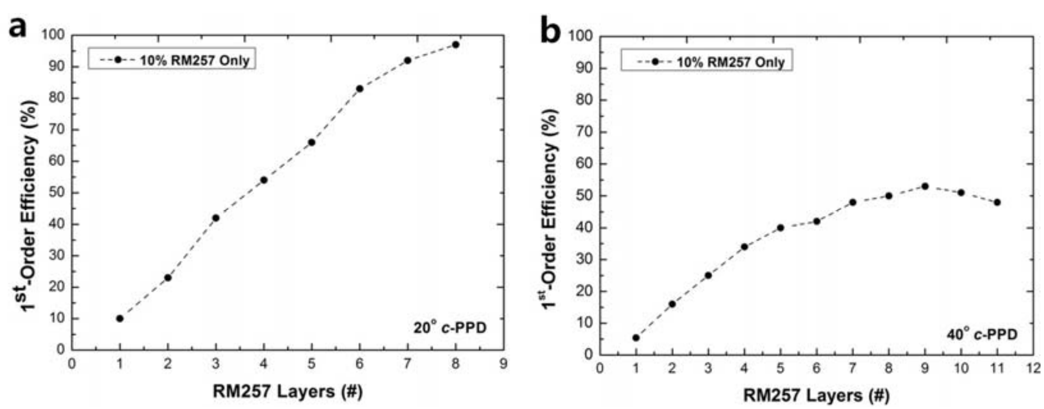

Figure 3 | Diffraction efficiency for a *c*-PPD. a, A *c*-PPD with 20^{o} deflection angle can achieve to 97% efficiency upon the increased retardation, which is realized by coating RM257 layers and tested using 633nm wavelegnth of laser. **b,** A *c*-PPD with 40° deflection angle can only achieve to ~50% efficiency experimentally tested using 633nm wavelength of laser.

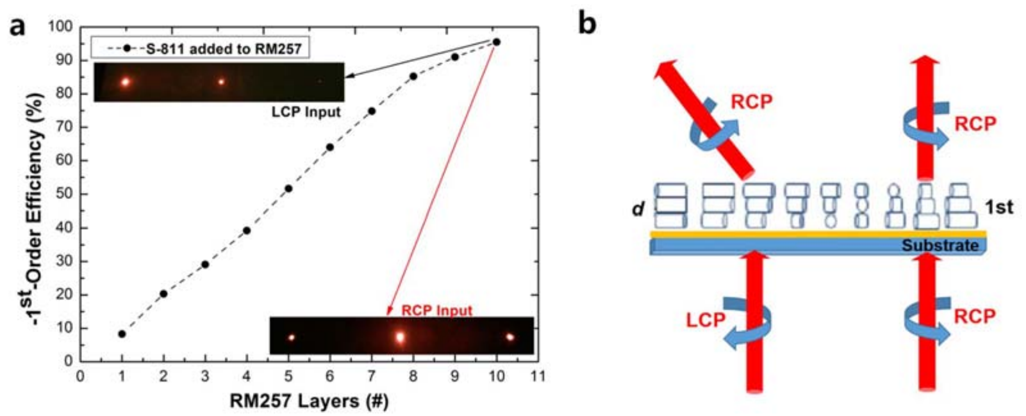

Figure 4 | Diffraction efficiency for a single DTPPD. a, The efficiency of 1st DTPPD upon the increased retardation is measured with input of LCP. Insets show photograph of the light intensity of each diffraction order with input of LCP/RCP after the 10th layer of RM257 is coated (photograph taken in a darkened room). **b,** The shematic of optical performance when LCP/RCP is as input to the 1st DTPPD as shown in Fig. 1b.

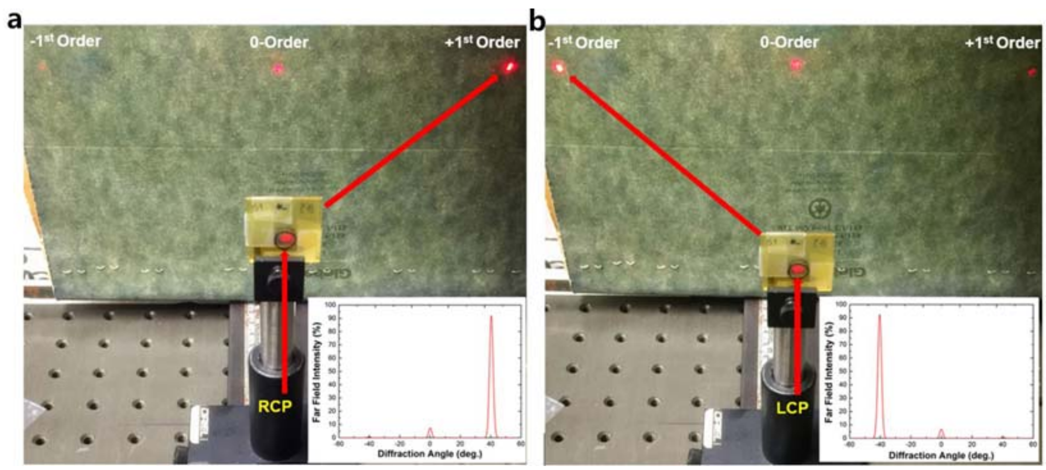

Figure 5 |Realization of a ±40° beam steering. a, By using the input of RCP, the red laser beam is diffracted to its +1st-order with +40° deflection angle with ~90% efficiency. **b,** By using the input of LCP, the red laser beam is diffracted to its −1st-order with −40° deflection angle with ~90% efficiency. Insets show the simulation result of far field intensity in both cases.